

The Light Scalar Mesons $a_0/f_0(980)$ at COSY-Jülich

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Abstract. The light scalar mesons $a_0/f_0(980)$ are being investigated at COSY-Jülich by detecting the strong decays into $K\bar{K}$ and $\pi\eta/\pi\pi$ as well as radiative decays into vector mesons. Selected results are discussed with emphasis on recent measurements at the ANKE and WASA spectrometers.

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PRODUCTION OF LIGHT SCALAR MESONS AT COSY

The COoler SYnchrotron COSY-Jülich provides proton and deuteron beams — phase-space cooled and polarized if desired — with momenta up to 3.7 GeV/c. It is thus well suited to produce the light scalars $a_0/f_0(980)$ since masses up to 1.1 (1.5, 1.03) GeV/c² can be produced in pp (pd , dd) collisions. Such hadronic interactions offer a few particular advantages:

- Due to large production cross sections rare processes, like radiative decays into vector mesons $a_0/f_0 \rightarrow \gamma V$ [1, 2, 3] or the isospin-violating a_0 - f_0 mixing [4, 5], are expected to occur at reasonable count rates.
- The isospin of the initial state and of the produced scalar meson can be selected. $pp \rightarrow dX^+$ or $pd \rightarrow tX^+$ reactions must lead to a_0^+ ($I=1$) production, a $pp \rightarrow ppX^0$, $pn \rightarrow dX^0$ (using a deuterium target) or a $pd \rightarrow {}^3\text{He}X^0$ reaction can produce both the a_0 and the f_0 , whereas the $dd \rightarrow {}^4\text{He}X$ process is a filter for the f_0 ($I=0$) resonance, because the initial deuterons and the α particle in the final state both have isospin $I=0$.
- For the $a_0/f_0 \rightarrow K\bar{K}$ decays the maximum accessible excess energy Q is rather small. Thus with a forward magnetic spectrometer like ANKE (see below), large acceptances and an unprecedented mass resolution $\delta_{m_{K\bar{K}}}$ can be reached. This is important to unravel effects induced by the opening of the K^+K^- and $K^0\bar{K}^0$ thresholds, which are separated by only 8 MeV/c².

At the same time the following drawbacks should be mentioned:

- Also the cross sections for background processes like multi-pion production are large.
- The final states contain at least two baryons. Therefore, the scalar meson signal can be distorted by final-state interactions (FSI) between these baryons and/or between one or more baryons and the mesons from a_0/f_0 decays. This effect has, *e.g.* been

seen for the $pp \rightarrow ppK^+K^-$ reaction [6] and also in $pd \rightarrow {}^3\text{He}K^+K^-$ data [7]. On the other hand such experiments can be exploited for the investigation of the low energy $\bar{K}N$ and $\bar{K}A$ interactions, see *e.g.* the analyses in Refs. [8, 9].

a_0/f_0 production has been or will be studied at COSY in pp , pn , pd and dd interactions for the strong decays into $K\bar{K}$ and $\pi\eta/\pi\pi$ as well as radiative decays γV into vector mesons. While near-threshold decay channels with at least one charged kaon can well be investigated with the magnetic spectrometer ANKE (“Apparatus for the detection of Nucleonic and Kaon Ejectiles”), the $\pi\eta$, $\pi\pi$ and γV final states will be measured with WASA (“Wide Angle Shower Apparatus”) which is available for measurements at COSY since 2007.

ANKE spectrometer

The magnetic ANKE spectrometer [10] consists of three dipoles and detection systems for identification of charged particles emitted under forward angles. For our measurements an H_2/D_2 cluster-jet target, which can provide areal densities of up to $5 \cdot 10^{14} \text{ cm}^{-2}\text{s}^{-1}$, has been used. Together with 10^{11} particles in the COSY ring, this corresponds to luminosities up to a few times $10^{31} \text{ cm}^{-2}\text{s}^{-1}$.

K^+ -mesons are detected in a positive side detection system [11], using time-of-flight (TOF) measurement between 23 scintillation start counters, which are placed near a side exit window of the spectrometer magnet, and the range telescopes system or a wall of scintillation counters. The momentum reconstruction algorithm uses the track information provided by two multiwire proportional chambers (MWPCs). This information as well as the kaon energy losses in the scintillators are used in order to suppress background. High momentum particles (p , d , t or He) produced in coincidence with the kaons are detected by a forward detection system which consists of three MWPCs (used for momentum reconstruction) and two layers of scintillation counters (particle ID). As a selection criteria, the energy loss of the particles and time difference between the hits in the side and forward systems are used. K^- -mesons are observed in a negative side detection system containing layers of scintillation counters and two MWPCs, which also provide the possibility to use the time difference between negative and positive detection systems, and ΔE techniques and to reconstruct K^- momenta [12].

WASA spectrometer

The 4π detector facility WASA [13] has been designed for studies of production and decays of light mesons. WASA makes use of a hydrogen and deuterium pellet target. The pellet concept is crucial to achieve a close to 4π detection acceptance in this internal target storage ring experiment. The target system provides small spheres of frozen hydrogen or deuterium and allows for high luminosities of up to $10^{32} \text{ cm}^{-2}\text{s}^{-1}$.

The WASA detectors comprise a forward part for measurements of charged target-recoil particles and scattered projectiles (p , d , t or He), and a central part for measurements of the scalar meson decay products. The forward part consists of eleven planes of

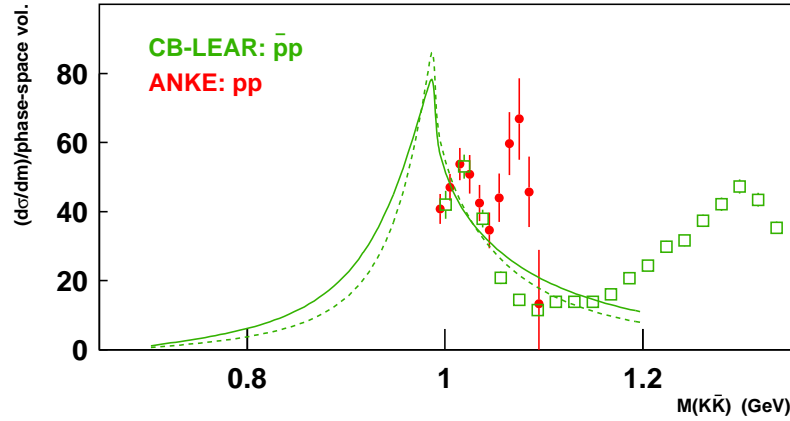


FIGURE 1. Invariant $K^+\bar{K}^0$ mass distributions normalized to the phase-space volume. The Crystal-Barrel data (open squares) are from the $\bar{p}p \rightarrow K_L K^\pm \pi^\mp$ reaction [16]; the ANKE data (full circles) for $pp \rightarrow dK^+\bar{K}^0$ at $Q = 105$ MeV [15]. The mass resolution of the ANKE data is $\delta_{m_{K\bar{K}}} = 3 \dots 10$ MeV/c² (FWHM). The lines denote the Flatté fits to Crystal-Barrel data from Refs. [16] (solid) and [17] (dashed).

plastic scintillators and of proportional counter drift tubes. The central part comprises an electromagnetic calorimeter with ~ 1000 CsI(Na) crystals surrounding a superconducting solenoid. Inside the solenoid a cylindrical chamber with drift tubes and a plastic scintillator barrel are placed.

THE $K\bar{K}$ FINAL STATE

Close-to-threshold data on kaon pair production in nucleon-nucleon scattering, like in the reactions $pp \rightarrow dK^+\bar{K}^0$ or $pp \rightarrow ppK^+K^-$, allow to study the $K\bar{K}$ and $\bar{K}N$ subsystems in the final state. The strength of the $K\bar{K}$ interaction is of relevance for a possible $K\bar{K}$ molecule interpretation of the scalar resonances $a_0(980)$ and $f_0(980)$. Similarly, a better understanding of the $\bar{K}N$ system is one prerequisite to infer the nature of the $\Lambda(1405)$.

The $pp \rightarrow dK^+\bar{K}^0$ reaction has been measured with ANKE at two proton kinetic energies $T_p = 2.65$ GeV, and 2.83 GeV, corresponding to excess energies of $Q = 48$ MeV and 105 MeV with respect to the $dK^+\bar{K}^0$ threshold [14, 15]. Figure 1 shows the invariant $K^+\bar{K}^0$ mass distribution (normalized to the phase-space volume) for the higher beam energy. The data seem to indicate a two-peak structure which clearly deviates from the expected Flatté-like behaviour for the a_0^+ resonance (indicated by the lines). While the enhancement at higher $K\bar{K}$ masses probably is a reflection of the $\bar{K}d$ FSI [18], there is no obvious interpretation of the lower one. Interestingly, the same peak structure (although, due to the lower mass resolution, only supported by the lowest-mass data point) is also observed for data from $\bar{p}p$ annihilations. A possible explanation of the unexpected shape is that interference effects by chance lead to the same structure in both data sets.

The measurements of the $pp \rightarrow ppK^+K^-$ reaction were performed at three energies

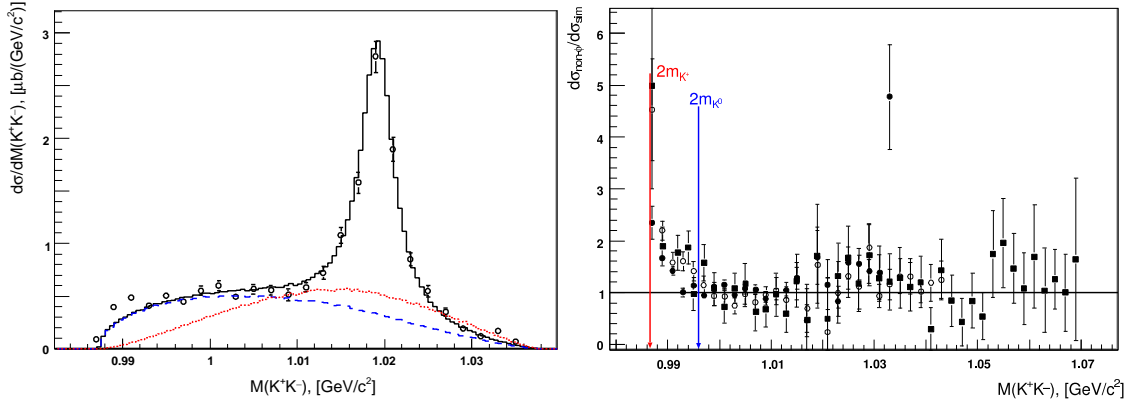


FIGURE 2. Left: Differential cross section for the $pp \rightarrow ppK^+K^-$ reaction with respect to the K^+K^- invariant mass at $T_p = 2.65$ GeV [6]. The solid (black) line shows the expected shape of the distribution from a Monte-Carlo simulation that takes into account the $\phi(1020)$, non- ϕ contributions as well as the $\bar{K}p$ and pp FSIs (best fit) [6]. For illustration, the dashed (blue) and dotted (red) lines show the shape of the non- ϕ mass distribution with the K^+K^- being in an S(P) wave. Right: Data for all measured energies 2.65 GeV, 2.70 GeV, and 2.83 GeV normalized to the best-fit distributions. The mass resolution is $\delta_{m_{K\bar{K}}} = 2 \dots 3$ MeV/c² (FWHM).

of $T_p = 2.65$ GeV, 2.70 GeV and 2.83 GeV, *i.e.* at Q values of 51 MeV, 67 MeV and 108 MeV with respect to the ppK^+K^- threshold. Figure 2 presents the invariant K^+K^- mass resolution for the lowest beam energy. The lines show the expected shape of the distribution from a Monte-Carlo simulation that takes into account the ANKE acceptance [6]. Three data points at the lowest $K\bar{K}$ masses lie significantly above the simulation. This behaviour is also visible for the other two beam energies and in DISTO results on the same reaction at $Q = 110$ MeV [19] as well as in our data on the $pn \rightarrow dK^+K^-$ reaction [20]. This effect is demonstrated in the right part of Fig. 2 where the ANKE differential cross section is normalized to the simulated spectra. At all three beam energies a significant enhancement between the K^+K^- and $K^0\bar{K}^0$ thresholds is observed.

The mass scale of the low-mass variation in Fig. 2 is not that of the widths of the scalar resonances, which are much larger. It is tempting to suggest that this structure might be due to the opening of the $K^0\bar{K}^0$ channel at a mass of 0.995 GeV/c², which induces some cusp structure that also changes the energy dependence of the total cross section near threshold. This would require a very strong $K^+K^- \rightleftharpoons K^0\bar{K}^0$ channel coupling, which might be driven by the a_0/f_0 resonances. Thus, although the $pp \rightarrow ppK^+K^-$ reaction may not be ideal for investigating the properties of scalar states, their indirect effects might still be crucial.

SEARCHES FOR ISOSPIN-SYMMETRY VIOLATION

An evident test of isospin symmetry is to scrutinize the a_0^0 and a_0^+ mass distributions. So far, the best knowledge of the a_0^0 shape comes from a Flatté fit to the $\pi^0\eta$ mass distribution from $p\bar{p}$ annihilations, measured with Crystal Barrel at LEAR [17]. The

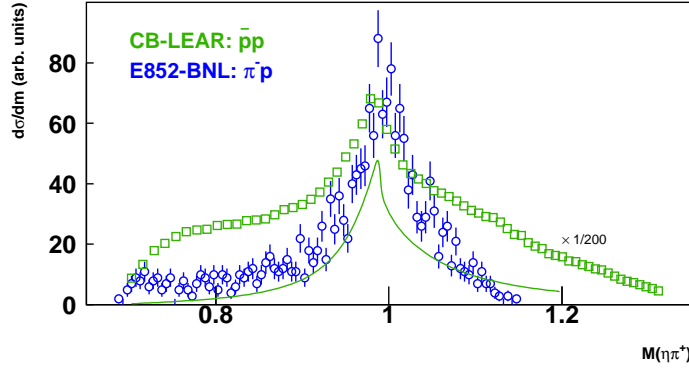


FIGURE 3. Invariant $\pi^0\eta$ mass distribution from $\bar{p}p \rightarrow \pi^0\eta\eta$ Crystal-Barrel data (green squares) [21] in comparison with that for the positive charge state $\pi^+\eta$ from pion-induced reactions (blue circles) [23]. The line denotes a Flatté fit from Ref. [17] to the Crystal-Barrel data.

fit yields the coupling constants with small statistical uncertainty, however, the $\pi^0\eta$ channel could, in principle, be distorted by isospin-violating a_0^0 - f_0 mixing effects, *e.g.* distortions of a basically symmetric Breit-Wigner type ($I=1, I_3=0$) a_0 mass distribution by admixtures of the ($I=0, I_3=0$) f_0 resonance. This effect might be sizable if the $\bar{p}p \rightarrow f_0 X$ cross section is significantly larger than for the a_0^0 [21, 22]

It is thus desirable to obtain high statistics data for the $I_3 = +1$ a_0^+ state, where mixing effects with the f_0 are strictly forbidden. The best data so far on the $a_0^+ \rightarrow \pi^+\eta$ decay from an experiment at BNL on pion-induced reactions [23] are displayed in Fig. 3 together with the above mentioned Crystal-Barrel data. The measured a_0^+ shape can as well be fitted by a Flatté distribution as by a Breit-Wigner (the latter corresponds to the case of zero coupling of the a_0^+ to kaons).

It has been predicted that a_0 - f_0 mixing can lead to a comparatively large isospin violation in the reactions $pd \rightarrow {}^3\text{He} a_0^0(\rightarrow \pi^0\eta)/f_0(\rightarrow \pi\pi)$ and $pd \rightarrow t a_0^+(\rightarrow \pi^+\eta)$ close to the corresponding production thresholds [24]. One may either test whether the cross-section ratios for these reactions follow isospin relations, or whether the a_0^0 and a_0^+ mass distributions exhibit different shapes. Both require data with high statistical accuracy for the strong scalar decay channels and background, *e.g.* from non-resonant $\pi\eta$ production must be well understood. A first test beam time took place in November 2007 at WASA and the data are currently being analyzed.

OUTLOOK

The $pd \rightarrow {}^3\text{He} a_0^0/f_0$ and $pd \rightarrow t a_0^+$ data that have been taken at WASA in November 2007 will also be used to search for events from radiative decays into vector mesons $a_0/f_0 \rightarrow \gamma V$. According to our estimates [3] a few thousand of such events could be measured in 10 weeks of beam time, however, scheduling of such a long beam time at COSY has to await the result of the above mentioned test measurement.

Another proposed measurement for WASA aims at data for the isospin-violating $dd \rightarrow {}^4\text{He}\pi^0\eta$ reaction [5]. That cross section is expected to be dominated by a primary reaction of the type $dd \rightarrow {}^4\text{He}f_0$, followed by an $f_0 \rightarrow a_0$ conversion, and an isospin-conserving $a_0 \rightarrow \pi^0\eta$ decay. In order to determine the $f_0 \rightarrow a_0$ mixing strength, the $dd \rightarrow {}^4\text{He}f_0$ production cross section must be experimentally determined. For that purpose, the $dd \rightarrow {}^4\text{He}K^+K^-$ reaction has been measured at ANKE. A preliminary analysis yields a total cross section in the range 50–100 pb. If that cross section is dominated by the $f_0 \rightarrow K^+K^-$ decay, then isospin violation in the $dd \rightarrow {}^4\text{He}\pi^0\eta$ reaction should be measurable at WASA within a few weeks of beam time.

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